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# General purpose cement with increased limestone content in Australia

Iman Mohammadi

*Cement Concrete & Aggregates Australia (CCAA), Sydney*

Warren J. South

*Cement Concrete & Aggregates Australia (CCAA), Sydney, [wsouth@uow.edu.au](mailto:wsouth@uow.edu.au)*

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# General purpose cement with increased limestone content in Australia

## Abstract

This paper discusses the effects of an increase in the maximum allowable limestone content of general purpose (GP) cement from 7.5 up to 12%. The substitution of a higher content of clinker with limestone will allow for a lower embodied energy and emissions associated with the manufacture of GP cement. Fresh and hardened properties of normal-grade concrete (N20 and N32) prepared with GP cement containing limestone contents in the range of 5 to 12% were investigated. The compliance of test results were checked and confirmed against the requirements of cement and concrete specifications. In addition, the test results were statistically examined, and no significant change in concrete properties was observed due to the change in limestone content. It is recommended that the allowable limestone content of GP cement be increased from 7.5 to 12%, resulting in an estimated 6% reduction in CO<sub>2</sub>eq emissions associated with cement manufacture.

## Keywords

general, australia, purpose, cement, increased, limestone, content

## Disciplines

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# General Purpose Cement with Increased Limestone Content in Australia

by Iman (James) Mohammadi and Warren South

*This paper discusses the effects of an increase in the maximum allowable limestone content of general purpose (GP) cement from 7.5 up to 12%. The substitution of a higher content of clinker with limestone will allow for a lower embodied energy and emissions associated with the manufacture of GP cement. Fresh and hardened properties of normal-grade concrete (N20 and N32) prepared with GP cement containing limestone contents in the range of 5 to 12% were investigated. The compliance of test results were checked and confirmed against the requirements of cement and concrete specifications. In addition, the test results were statistically examined, and no significant change in concrete properties was observed due to the change in limestone content. It is recommended that the allowable limestone content of GP cement be increased from 7.5 to 12%, resulting in an estimated 6% reduction in  $CO_{2eq}$  emissions associated with cement manufacture.*

**Keywords:** compressive strength; drying shrinkage; fresh and hardened properties; general purpose (GP) cement; limestone; setting time; sustainable cement.

## INTRODUCTION

Historically, the manufacture of portland cement has been viewed in emissions of carbon dioxide ( $CO_2$ ). This is driven by the calcination of limestone, the combustion of fossil fuels, and the use of electricity in cement production processes,<sup>1</sup> as shown in Fig. 1.

Using current technology and processes,  $CO_2$  emissions are difficult to avoid, as the manufacturer of cement making relies on the calcination of limestone. Approximately 55% of total carbon dioxide emissions from the cement manufacturing process are associated with calcination of clinker. Therefore, a reduction in the content of cement clinker would result in a reduction of total emissions. One of the most readily accessible strategies for the cement manufacturers to reduce emissions from cement production is to substitute clinker with limestone. Limestone is the major ingredient in the production of clinker and is usually available in large quantities at clinker manufacturing plants. However, in the Australian context, it worth noting that limestone used as a mineral addition must be of a quality that it complies with Australian Standards. This may only constitute a fraction of total limestone supply in a cement plant.

In Australia, a little over 25% reduction in emissions has been achieved since 1990.<sup>2</sup> However, with community requirements influencing the use of alternative fuels, limited opportunity for thermal and electrical efficiency gains due to the relative young age of cement manufacturing equipment, and little or no exploration of Carbon Capture & Storage strategies (CCS), clinker substitution remains the only viable alternative for emissions reduction.

An enhancement in the production process and the closure of aging production facilities has made some contribution

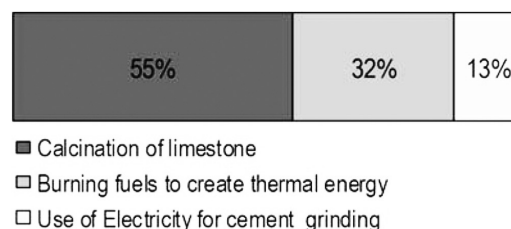


Fig. 1—Source of  $CO_2$  emissions in typical cement plant.

to lowering embodied emissions in Australia. However, the greatest contribution has come from the use of limestone and other substitutes to clinker such as slag and fly ash. Since 2010, the Australian Standard AS 3972 allows such changes in composition through the substitution of clinker with minerals to occur. General purpose (GP) cement is the most commonly used cement in Australia. To achieve ongoing reductions in  $CO_2$  emissions associated with the production of cement, an increase in mineral addition of GP cement is required.

This research investigates the appropriate maximum level of clinker substitution in GP cement. This is due to the fact that the Australian Standard allows a small range of cements compared to other countries, and is a relatively smaller diverse market than Europe or North America. In Australia, the introduction of a new type of cement, such as limestone-blended cement, is not practical due to capital costs associated with changes in production lines and the small size of the cement industry. It is very critical to take into account that, in contrast to the Europe and the United States, there is no economical ability to deliver a separate cement supply stream in Australia.

The production of a new type of cement, such as general limestone purpose (GL) cement, requires significant capital investment, estimated to be upward of \$200 million, especially for the installation of new silos in cement plants. According to current industry cost data collected from the seven major Australian cement plants, including Gladstone (Cement Australia), Railton (Cement Australia), Angaston (Adelaide Brighton), Birkenhead (Adelaide Brighton), Maldon (Boral Cement), Berrima (Boral Cement), and Munster (Cockburn Cement), an increase in the maximum allowable limestone content of the current GP cement, is recognized to be the most viable solution that cement industry can apply, without requiring significant capital investment.

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Tennis et al.<sup>3</sup> reported that the use of mineral additions reduces the embodied emissions in cement roughly in proportion with the reduction in clinker; therefore, by increasing the limestone content of cement from 7.5 to 12%, as suggested by this research, CO<sub>2</sub> emissions per tonne of cement production should decrease by at least 4.5%. However, on further analysis, the actual decrease in CO<sub>2</sub> emissions is estimated to be higher. This is due to the fact that a number of cement plants have not increased the allowable mineral content of their cement from 5 to 7.5%, permitted by the revision of AS 3972 in 2010. The 2.5% change (from 5 to 7.5%) in mineral addition was not significant enough for all cement plants to adjust their production line in response to the revision. The suggested 12% limit, however, is considered large enough to initiate production line adjustments.

General purpose (GP) cement is the most common commercially used cement in Australia and accounts for over 85% of the total cement market for production of concrete. This research program included all major cement plants throughout Australia. In a new approach, cement samples of different limestone content were manufactured in actual cement plant facilities and not in laboratories. It has been proven that limestone mineral content of up to 5% in portland cement has positive effects on properties of cement and concrete.<sup>4</sup> A unique feature of this study is to increase the allowable maximum minerals addition of GP cement to 12%, while it is currently limited to 5% for other international equivalent cement types such as CEM I 32.5N and CEM I 42.5N in Europe and Cement Type I ASTM C150 in the United States. The increased content of mineral addition provides for a more sustainable GP cement, while at the same time does not compromise the structural properties and durability of concrete. Moreover, this study investigates the effect of the increased limestone content on different properties of concrete by performing tests on samples prepared by commercial normal-grade mixture design, N20 and N32, acquired from the major concrete suppliers.

## RESEARCH SIGNIFICANCE

This paper discusses the results of an extensive experimental study to provide sufficient evidence to support the increase of the maximum allowable mineral content of GP cement from 7.5 to 12%. It is estimated that when applies this change results in an up to 6% decrease in associated CO<sub>2</sub> emissions, while the performance of normal-grade concrete is not diminished. In addition, an increase in limestone content does not require any major capital investment from the cement industry.

## LITERATURE REVIEW

The effects of an increased limestone content of cement on fresh and hardened properties of concrete have been discussed by previous studies. This includes concrete fresh properties such as workability, air content, and bleed water, as well as concrete hardened properties such as setting times, compressive strength, and drying shrinkage.

Chen et al.<sup>5</sup> reported that the substituting cement content with limestone in the range of up to 37% resulted in lower water demand or improved workability of concrete mixtures,

whereas a number of authors have observed slight increases in water demand or water reducer due to an increase in limestone content in the range of 5 to 35%.<sup>6-10</sup> Moreover, Meddah et al.<sup>11</sup> discussed that limestone content in the range of up to 45% had no significant effect on concrete slump. Sotiriadis et al.<sup>12</sup> observed a similar slump for mixtures with limestone content of 15% when the workability of samples with limestone in the range of 15 to 35% were examined. Research conducted by the Building Research Establishment (BRE) shows that the bleed rate (and the total amount of bleed water) is highly dependent on the surface area of the binder and independent of the amount of limestone mineral substitution.<sup>13</sup>

Yahia et al.<sup>9</sup> noted that limestone in the range of up to 40% could be used to improve the packing density of the aggregates and reduce the volume of voids to be filled. It is reported that this improvement in packing of concrete aggregates resulted in lower permeability, porosity, and air content.<sup>5</sup> It was hypothesized in the literature that the fine carbonate from the limestone enhanced the number of contact points between hydration products and improved the packing density of the microstructure. Sotiriadis et al.<sup>12</sup> showed that control samples and samples prepared with 15 and 35% limestone cement had similar air contents in the range of  $1.9 \pm 0.3\%$ . Similar results are presented by Bosiljkov<sup>14</sup> for self-consolidating mixtures prepared using high limestone content in the range of up to 50%. Bosiljkov<sup>14</sup> showed that the air content of concrete mixtures containing limestone in the range of 25 to 50% were in the range of  $1.3 \pm 0.6\%$  for control samples. Valcuende et al.<sup>15</sup> inferred the same conclusion—that air content does not appear to depend on the limestone content added to the mixture when it is in the range of up to 30%.

With regard to setting time, previous studies are inconsistent in discussing the effect of increased limestone. Some studies show that at high levels of limestone substitution (that is, over 15%), the paste setting time may be reduced compared to a portland cement prepared with no limestone addition.<sup>16-19</sup> However, a number of other studies reported that replacing cement with limestone in the range of up to 18,<sup>20</sup> 35,<sup>21</sup> or 45%<sup>22</sup> resulted in the increase in the initial or final setting times.

Different studies report that cement with an increased limestone content, ranging from 5 to 15%, can be used to produce a full range of concrete and mortar strengths.<sup>23,24</sup> Others found that limestone in the range of up to 55% may increase compressive strength in early ages.<sup>5,19,25</sup> However, a number of studies have reported a reduction in compressive strength by substituting cement with limestone in the range of up to 45% and specifically for substitution levels in excess of 15%.<sup>6,11,12,26,27</sup>

Dhir et al.<sup>28</sup> reported that the limestone mineral addition decreases the measured drying shrinkage. The decrease in drying shrinkage by substituting clinker with limestone in the range of up to 45% is also confirmed by other studies.<sup>11,29</sup> Similarly, studies conducted by Bucher et al.<sup>30</sup> and Bentz et al.<sup>31</sup> confirmed similar or less shrinkage for the cement substitution range with limestone of up to 10%. Bucher et al.<sup>30</sup> discussed that autogenous, unrestrained, and restrained shrinkage were

all reduced as limestone content is increased to 20%, which could be attributed to the better particle size distribution and reduction of cement in the paste.<sup>28</sup> It was also discussed by Bouasker et al.<sup>32</sup> that the increase in the dosage of limestone filler from 10 to 20% resulted in delaying the appearance of the first crack in concrete samples. Other studies found almost similar or less shrinkage for samples containing low limestone contents in the range of up to 16%.<sup>33-35</sup> Marzouki et al.<sup>36</sup> examined samples containing increased limestone up to 35% and reported that the limestone content of cement has no real influence on shrinkage over longer time periods, where the dry shrinkages are essentially equivalent regardless of the limestone content in cement.

## EXPERIMENTAL PROGRAM

### Experimental methodology

The research methodology is based on the statistical evaluation of the effect of higher limestone in GP cement, which involved three stages. The first stage is investigating any correlation (evident trend) between the populated test results and limestone content of cement. The second stage is checking the compliance of the test results of increased limestone contents with the Australian standards and industry specifications. The third stage is investigating if any significant change in properties of normal-grade (N20 and N32) concretes is due to the increased limestone content of GP cement. The selected research methodology is congruent with the research “Specifications and Protocols for Acceptance Tests on Processing Additions in Cement Manufacturing” conducted by National Cooperative Highway Research Program in the United States.<sup>37</sup>

The hypothesis test was carried out at confidence level of 95%, and with the following “null” and “research” hypotheses. The research hypothesis, symbolized  $H_1$ , states that the introduction of 12% limestone to GP cement does alter the characteristics of the normal-grade concrete by more than 2%. The null hypothesis, symbolized  $H_0$ , states that the introduction of 12% limestone to GP cement does not change the characteristics of the concrete by more than 2%.

### Experimental materials

In cement plants, clinker was ground with gypsum and limestone to form the final cement product. Limestone was obtained from local resources throughout Australia and was ground with clinker to produce cement with different limestone contents in the range of 5 to 12%. Selected limestone types in different cement plants contained no less than 75% by mass of  $\text{CaCO}_3$  as prescribed by local and international standards. The Canadian Standard CSA A3001 has a minimum limit of  $\text{CaO}_3$  of 75% in the limestone and ASTM C150 has a requirement of at least 70% by mass of  $\text{CaO}_3$ . The limestone types used are therefore internationally compliant. Moreover, in the Australian context, limestone with  $\text{CaCO}_3$  content equal to or greater than 75% and less than 80% is acceptable, provided the clay content determined by the methylene blue test, as given in EN 933-9 test method, does not exceed 1.20%, and the total organic carbon (TOC) content, as given in EN 13639 test method, does not exceed 0.50% by mass.

It was decided to test a wide range of commercial normal-grade concrete mixtures. The aim of this research was to examine a true population representing the currently used normal-grade mixture designs by the commercial construction industry in Australia rather than testing limited laboratory mixed concrete samples. Table 1 provides information on the binder composition of the 19 commercial mixture designs used for the production of normal-grade N20 and N32 concretes. Both grades are prepared by using obtained mixture designs from the concrete industry and cement manufactured in cement plants of differing limestone content. In total, 19 mixture designs were acquired for this research program, including 67 mixture series at different limestone contents. Concrete samples Grade 20 MPa (2900 psi) were prepared using commercial mixture designs with constituents as follows:

- Water-cement ratio ( $w/c$ ) ratio in the range of 0.58 to 0.71 and for N20 mixtures prepared with only binder GP: cement content of 240 to 310  $\text{kg/m}^3$  (400 to 523  $\text{lb/yd}^3$ ), and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1100  $\text{kg/m}^3$  (1517 to 1854  $\text{lb/yd}^3$ ), respectively.
- N20 mixtures with binder GP and fly ash: total cementitious content of 240 to 350  $\text{kg/m}^3$  (400 to 590  $\text{lb/yd}^3$ ), and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1100  $\text{kg/m}^3$  (1517 to 1854  $\text{lb/yd}^3$ ), respectively.
- N20 mixtures with binder GP, fly ash, and slag: total cementitious content of 240 to 335  $\text{kg/m}^3$  (400 to 565  $\text{lb/yd}^3$ ), and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1100  $\text{kg/m}^3$  (1517 to 1854  $\text{lb/yd}^3$ ), respectively.

Concrete samples Grade 32 MPa (4641 psi) were prepared using commercial mixture designs with constituents as follows:

- Water-cement ratio ( $w/c$ ) ratio in the range of 0.47 to 0.61 and for N32 mixtures with only binder GP: cement content of 280 to 350  $\text{kg/m}^3$  (472 to 590  $\text{lb/yd}^3$ ) and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1200  $\text{kg/m}^3$  (1517 to 2023  $\text{lb/yd}^3$ ), respectively.
- N32 mixtures with binder GP and fly ash: total cementitious content of 280 to 380  $\text{kg/m}^3$  (472 to 641  $\text{lb/yd}^3$ ), and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1200  $\text{kg/m}^3$  (1517 to 2023  $\text{lb/yd}^3$ ), respectively.
- N32 mixtures with binder GP, fly ash, and slag: total cementitious content of 280 to 380  $\text{kg/m}^3$  (472 to 640  $\text{lb/yd}^3$ ), and local fine and coarse content in the range of 700 to 900  $\text{kg/m}^3$  (1180 to 1517  $\text{lb/yd}^3$ ) and 900 to 1200  $\text{kg/m}^3$  (1517 to 2023  $\text{lb/yd}^3$ ), respectively.

As can be seen from Table 1, 67 concrete mixtures included 32 normal grades of N20 and 35 normal grades of N32, which were prepared with cement containing limestone in the range of 4.5% to 12%.

Tests were carried out in three different industrial laboratories, labeled A, B, and C. Performing tests in different laboratories minimizes the effects of the test operators and facilities on the final results. All involved laboratories had the Australian National Association of Testing Authorities



**Table 1—General information of different combinations of tested GP cement**

Nominated binder	Laboratory label	Cement composition, %			Initial cement limestone content, %	Tested contents of limestone, %
		GP cement	Fly ash	Slag		
Normal Grade N20 ( $f'_c = 20$ MPa [2900 psi])						
20-A-GP100-1	Lab A	100	—	—	5.0	5, 10
20-B-GP100-2	Lab B	100	—	—	5.0	5, 7.5, 10, 12
20-B-GP100-3	Lab B	100	—	—	5.0	5, 7.5, 10, 12
20-B-GP75FA25-4	Lab B	75	25	—	5.0	5, 7.5, 10, 12
20-B-GP75FA25-5	Lab B	75	25	—	5.0	5, 7.5, 10, 12
20-B-GP55FA25S20-6	Lab B	55	25	20	5.0	5, 7.5, 10, 12
20-B-GP55FA25S20-7	Lab B	55	25	20	5.0	5, 7.5, 10, 12
20-C-GP75FA25-8	Lab C	75	25	—	4.5	4.5, 10, 12
20-C-GP75FA25-9	Lab C	75	25	—	4.5	4.5, 10, 12
Normal Grade N32 ( $f'_c = 32$ MPa [4641 psi])						
32-A-GP100-1	Lab A	100	—	—	5.0	5, 10
32-B-GP100-2	Lab B	100	—	—	5.0	5, 7.5, 10, 12
32-B-GP100-3	Lab B	100	—	—	5.0	5, 7.5, 10, 12
32-B-GP75FA25-4	Lab B	75	25	—	5.0	5, 7.5, 10, 12
32-B-GP75FA25-5	Lab B	75	25	—	5.0	5, 7.5, 10, 12
32-B-GP55FA25S20-6	Lab B	55	25	20	5.0	5, 7.5, 10, 12
32-B-GP55FA25S20-7	Lab B	55	25	20	5.0	5, 7.5, 10, 12
32-C-GP100-8	Lab C	100	—	—	4.5	4.5, 10, 12
32-C-GP75FA25-9	Lab C	75	25	—	4.5	4.5, 10, 12
32-C-GP60FA40-10	Lab C	60	40	—	4.5	4.5, 10, 12

(NATA) certification, ensuring the consistency competence of test results in terms of reproducibility and repeatability.

This research program required the manufacture of cements at different cement plants. Due to production and market requirements, this was possible at four plants using different grinding circuits and raw materials. Not all manufacturers were able to produce up to the maximum limestone addition of 12% due to equipment limitations; therefore, for two sets (20-A-GP100-1 and 32-A-GP100-1), the maximum content of limestone for the produce GP cement samples was limited to 10%, whereas it is 12% for the other 17 sets, as shown in Table 1. The physical and chemical properties of tested cement due to change of limestone content are presented in Table 2. Results were compared with the Australian requirements for GP cement stated in the Australian Standard AS 3972. In addition, cement properties were compared with requirements of the international standards, including CEM I (32.5 N and 42.5N) and ASTM C150 Type I. As it can be seen from the results presented in Table 2, cement containing 12% limestone complied with the requirements of the Australian and international standards.

## RESULTS AND DISCUSSION

Normal-grade concretes, using Type GP cement manufacturing with a limestone content of up percentage of up to 12% and local aggregates from five different states, were prepared. The effect of the higher limestone content on fresh and hardened properties of concrete, including slump, air content, setting times, bleed water, as well as compressive

strength and drying shrinkage, was then examined. Results from the test program are provided in Table 3. Results from each set of concrete were compared to the relevant results from control samples. The effects of the increased limestone content of cement were investigated through investigating the relative change in concrete properties against the concrete samples (Fig. 2 to 5). In all cases, control samples were prepared using cement containing 4.5 to 5% limestone. AS 3972 specifies the maximum allowable limestone content of 7.5% in GP cement, therefore, the investigation of relative changes to the control samples with 4.5 to 5% limestone is considered a conservative evaluation.

Figures 2(a) and 3(a) show an insignificant negative correlation between the slump (workability) of concrete samples and limestone content for cement of both grades, N20 and N32. However, the results show very low  $R^2$  without any evident trend. It is important to consider that normal-grade concrete has target slump of  $80 \pm 10$  mm ( $3.15 \pm 0.4$  in.). Although a change of 10% in slump numbers is considered statistically significant, in reality the reproducibility of slump test and the tolerance range for the results makes such change practically insignificant.

Similarly, it can be seen from Fig. 2(b), (d), and (e) as Fig. 3(b), (d), and (e) that air content and setting times for concrete samples were not influenced by the increased limestone from 5 to 12%. However, better performance in term of cohesiveness and workability was observed for mixtures with an increased limestone content. There is a negative correlation between concrete slump, air content, and setting

**Table 2—Test methods and requirements for compliance of cement and mortar with local and international standards**

Properties	Unit	Research testing framework			CEM I 32.5N	CEM I 42.5N	ASTM C150 Type I	Cement limestone content, %			
		Method	Limit	Description				5 control	7.5	10	12
Mineral addition	%	AS 3972	<7.5	All cement	≤5	≤5	≤5	5	7.5	10	12
Surfer SO <sub>3</sub> content	%	AS 2350.2	<3.5	All cement	≤3.5	≤3.5	≤3.0*	2.57	2.50	2.45	2.68
Chloride content	%	AS 2350.2	<0.1	All cement	≤0.10	≤0.10	≤0.10	0.014	0.013	0.015	0.014
Alkali content	%	AS 2350.2	—	—	—	—	≤0.6†	0.32	0.20	0.25	0.09
Loss on ignition	%	AS 2350.2	—	—	≤5‡	≤5‡	≤3‡	3.14	4.30	5.07	6.08
Insoluble residue	%	AS 2350.2	—	—	≤5	≤5	≤0.75	5.48	2.40	4.95	5.85
Initial setting time	min	AS 2350.4	>45	Type GP	≥60	≥75	≥75	113	127	107	112
Final setting time	min	AS 2350.4	<360	Type GP	≤360	—	—	194	210	181	184
Soundness	%	AS 2350.5	<5.0	All cement	≤10	≤10	NA§	1	1	1	1
Fineness	m <sup>2</sup> /kg (ft <sup>2</sup> /lb)	AS 2350.8	—	—	—	—	≥260 (1269)	379 (1850)	379 (1850)	420 (2051)	458 (2236)
Peak temperature rise	°C (°F)	AS 2350.7	<23 (73)	Type LH	—	—	—	29 (84)	—	30 (86)	34 (93)
7-day CS <sup>  </sup>	MPa (psi)	AS 2350.11	>35.0 (5076)	Type GP	≥16 (2320)	—	≥19 (2756) <sup>#</sup>	47.6 (6903)	50.1 (7266)	46.5 (6744)	46.3 (6715)
28-day CS	MPa (psi)	AS 2350.11	>45.0 (6526)	Type GP	≥32.5 (4713)**	≥42.5 (6164)**	≥28 (4061) <sup>#</sup>	37.8 (5482)	36.9 (5352)	37.0 (5366)	36.9 (5352)
7-day CS	MPa (psi)	AS 2350.11	>20.0 (2901)	Type GB	—	—	—	60.3 (8745)	61.7 (8948)	57.4 (8325)	56.9 (8252)
28-day CS	MPa (psi)	AS 2350.11	>35.0 (5076)	Type GB	—	—	—	57.1 (8281)	56.3 (8165)	54.2 (7861)	55.2 (8006)
28-day DS	με	AS 2350.13	<750	Type SL	—	—	—	589	550	582	589
16-week SE	με	AS 2350.14	<750	Type SR	—	—	—	387	457	695	416

\*It should be ≤3.0 for cement with C<sub>3</sub>A ≤ 8% and ≤3.5 for cement with C<sub>3</sub>A > 8%.

†When cement is to be used in concrete with aggregates that are potentially reactive, total alkali limit should be considered.

‡Presented limits are for cements with less than 5% limestone content. ASTM C595 limits cement LOI for blended cement with limestone to a maximum of 10%.

§Limit is for autoclave expansion test.

||CS is compressive strength; DS is drying shrinkage; and SE is sulfate expansion.

#Compressive test should be conducted with 50 x 50 x 50 mm (2 x 2 x 2 in.) cubes.

\*\*≥32.5 and ≤52.5 MPa (≥4714 and ≤7614 psi); compressive test should be conducted with ISO prisms.

††≥42.5 and ≤62.5 MPa (≥6164 and ≤9065 psi); compressive test should be conducted with ISO prisms.

Notes: 1 m<sup>2</sup>/kg = 4.88 ft<sup>2</sup>/lb; 1 MPa = 145 psi.

times and the increase of limestone, but the established correlation is not strong and considered insignificant. The only evident trend was the negative correlation between the amount of bleed water and limestone content, as shown in Fig. 2(c) and 3(c). The lower bleed water results shows the effect of higher fineness of cement samples with higher limestone content. Tennis et al.<sup>3</sup> reported that the limestone portion is generally more finely ground than clinker because it is softer and more easily ground. Results presented in Table 2 confirmed that, by increasing limestone content from 5 to 12%, fineness was increased from 379 to 458 m<sup>2</sup>/kg (638 to 772 lb/yd<sup>3</sup>). The resulting increase in fineness is congruent with the literature that showed bleed water is highly dependent on the surface area of the binder, and independent of the amount of limestone mineral substitution.<sup>13</sup> The effect of limestone on bleed water may control excessive bleed and facilitate finishing of concrete pavements in some cases. Bleed water is not a primary design characteristic in mixture design procedures compared to the

slump, compressive strength, and drying shrinkage. The negative correlation was more evident for Grade N32, which can attributed to the result of the higher cement content for Grade N32 samples compared to test results of Grade N20.

Analysis of the compressive strength test results for both Grades N20 and N32, and at different testing ages, revealed that except for the early ages, the effect of substituting cement with limestone in the range of 5 to 12% was neutral, as presented in Fig. 4(d) and (e) and Fig. 5(d) and (e). Test results at early ages of 1, 3, and 7 days demonstrated positive correlations between the limestone content of cement and concrete strength shown in Fig. 4(a) to (c) and Fig. 5(a) to (c). However, the improving effect of limestone on the early-age strength was not significant. The test results were scattered, and the positive correlation is considered insignificant. In summary, there is no significant correlation between concrete strength and limestone content up to 12%.

Drying shrinkage results showed a minor increase in drying shrinkage for concrete samples with an increased

**Table 3—Test results for normal grades of concrete, N20 and N32**

Nominated binder	Lime-stone, %	Slump, mm (in.)	Setting, min		AC, %	Bleed, %	Compressive strength, MPa (psi)					Drying shrinkage, $\mu\epsilon$
			Initial	Final			1-day	3-day	7-day	28-day	56-day	
Normal Grade N20 ( $f'_c = 20$ MPa [2900 psi])												
20-A-GP100-1 (Control)	5	85 (3.3)	450	645	5.0	—	6.0 (870)	13.5 (1958)	17.0 (2466)	27.0 (3916)	32.0 (4641)	600
20-A-GP100-1	10	85 (3.3)	390	510	5.0	—	6.0 (870)	13.0 (1885)	16.0 (2320)	26.5 (3843)	28.5 (4133)	650
20-B-GP100-2 (Control)	5	80 (3.1)	380	490	4.4	5.8	—	18.0 (2611)	23.5 (3408)	29.0 (4206)	31.5 (4568)	550
20-B-GP100-2	7.5	80 (3.1)	420	520	4.5	5.8	—	18.0 (2611)	24.8 (3597)	30.0 (4351)	31.5 (4568)	500
20-B-GP100-2	10	70 (2.8)	370	480	3.7	4.6	—	19.5 (2828)	23.5 (3408)	29.5 (4278)	31.0 (4496)	530
20-B-GP100-2	12	70 (2.8)	370	460	3.7	4.3	—	21.0 (3046)	26.0 (3771)	31.5 (4568)	32.0 (4641)	530
20-B-GP100-3 (Control)	5	75 (2.9)	—	—	4.5	—	—	17.0 (2466)	21.8 (3162)	28.3 (4104)	30.0 (4351)	530
20-B-GP100-3	7.5	75 (2.9)	—	—	4.6	—	—	17.5 (2538)	23.8 (3452)	29.2 (4235)	30.5 (4423)	520
20-B-GP100-3	10	75 (2.9)	—	—	4.0	—	—	17.3 (2509)	23.0 (3336)	27.8 (4032)	29.5 (4278)	540
20-B-GP100-3	12	80 (3.1)	—	—	4.0	—	—	18.5 (2683)	24.0 (3481)	28.7 (4162)	30.5 (4423)	510
20-B-GP75FA25-4 (Control)	5	80 (3.1)	440	550	3.0	7.6	—	13.0 (1885)	17.5 (2538)	27.0 (3916)	33.0 (4786)	480
20-B-GP75FA25-4	7.5	75 (2.9)	470	580	3.0	7.3	—	13.0 (1885)	17.5 (2538)	27.7 (4017)	34.3 (4975)	420
20-B-GP75FA25-4	10	80 (3.1)	440	560	3.0	6.0	—	13.0 (1885)	17.5 (2538)	26.8 (3887)	32.3 (4684)	440
20-B-GP75FA25-4	12	80 (3.1)	480	590	3.1	8.1	—	14.5 (2103)	18.3 (2654)	27.7 (4017)	33.8 (4902)	390
20-B-GP75FA25-5 (Control)	5	80 (3.1)	—	—	3.2	—	—	13.0 (1885)	17.5 (2538)	27.0 (3916)	32.8 (4757)	400
20-B-GP75FA25-5	7.5	80 (3.1)	—	—	3.3	—	—	12.0 (1740)	16.3 (2364)	25.7 (3727)	31.5 (4568)	440
20-B-GP75FA25-5	10	80 (3.1)	—	—	3.1	—	—	12.3 (1784)	16.0 (2320)	25.7 (3727)	31.5 (4568)	470
20-B-GP75FA25-5	12	80 (3.1)	—	—	3.3	—	—	12.3 (1784)	16.5 (2393)	25.2 (3655)	30.8 (4467)	450
20-B-GP55FA25S20-6 (Control)	5	85 (3.3)	490	620	3.2	7.6	—	8.6 (1247)	13.5 (1958)	27.2 (3945)	32.5 (4713)	530
20-B-GP55FA25S20-6	7.5	90 (3.5)	510	660	3.4	9.6	—	8.5 (1233)	14.5 (2103)	27.2 (3945)	31.0 (4496)	520
20-B-GP55FA25S20-6	10	80 (3.1)	500	630	3.2	10.9	—	9.1 (1320)	14.3 (2074)	28.7 (4162)	33.3 (4829)	590
20-B-GP55FA25S20-6	12	75 (2.9)	480	610	3.0	6.4	—	9.1 (1320)	16.5 (2393)	27.5 (3988)	32.5 (4713)	590
20-B-GP55FA25S20-7 (Control)	5	80 (3.1)	—	—	3.4	—	—	8.2 (1189)	12.5 (1813)	27.3 (3959)	31.3 (4539)	510
20-B-GP55FA25S20-7	7.5	70 (2.8)	—	—	3.4	—	—	8.7 (1262)	15.3 (2219)	28.7 (4162)	33.8 (4902)	610
20-B-GP55FA25S20-7	10	80 (3.1)	—	—	3.3	—	—	7.9 (1146)	13.5 (1958)	26.0 (3771)	30.8 (4467)	630
20-B-GP55FA25S20-7	12	75 (2.9)	—	—	3.4	—	—	9.1 (1320)	15.3 (2219)	29.2 (4235)	33.3 (4829)	580
20-C-GP75FA25-8 (Control)	4.5	75 (2.9)	465	605	4.1	5.4	4.4 (638)	13.3 (1929)	17.3 (2509)	25.3 (3669)	33.4 (4844)	490
20-C-GP75FA25-8	10	75 (2.9)	445	585	4.7	4.8	4.2 (609)	12.6 (1827)	16.8 (2437)	25.1 (3640)	30.8 (4467)	470
20-C-GP75FA25-8	12	75 (2.9)	435	555	4.3	4.2	4.6 (667)	12.2 (1769)	15.6 (2262)	23.1 (3350)	32.0 (4641)	490
20-C-GP75FA25-9 (Control)	4.5	75 (2.9)	465	590	4.7	5.4	3.7 (537)	12.2 (1769)	15.4 (2233)	25.0 (3626)	32.0 (4641)	470
20-C-GP75FA25-9	10	80 (3.1)	460	585	4.7	5.0	4.0 (580)	11.1 (1610)	15.3 (2219)	24.6 (3568)	31.6 (4583)	470
20-C-GP75FA25-9	12	70 (2.8)	440	560	4.3	4.2	4.8 (696)	12.4 (1798)	16.0 (2320)	24.5 (3553)	33.8 (4902)	460
Normal Grade N32 ( $f'_c = 32$ MPa [4641 psi])												
32-A-GP100-1 (Control)	5	85 (3.3)	420	570	2.0	—	10.0 (1450)	22.0 (3191)	28.5 (4133)	39.5 (5729)	45.0 (6526)	640
32-A-GP100-1	10	85 (3.3)	330	450	2.0	—	10.0 (1450)	20.5 (2973)	27.5 (3988)	38.5 (5584)	46.0 (6671)	670
32-B-GP100-2 (Control)	5	85 (3.3)	350	430	3.8	5.1	—	25.5 (3698)	32.0 (4641)	39.2 (5685)	40.0 (5801)	580



**Table 3 (cont.)—Test results for normal grades of concrete, N20 and N32**

Nominated binder	Lime- stone, %	Slump, mm (in.)	Setting, min		AC, %	Bleed, %	Compressive strength, MPa (psi)					Drying shrinkage, με
			Initial	Final			1-day	3-day	7-day	28-day	56-day	
Normal Grade N32 ( $f'_c = 32$ MPa [4641 psi])												
32-B-GP100-2	7.5	75 (2.9)	350	440	3.6	3.8	—	26.3 (3814)	34.0 (4931)	40.8 (5917)	43.0 (6236)	570
32-B-GP100-2	10	80 (3.1)	350	440	3.6	4.2	—	25.8 (3742)	31.3 (4539)	39.0 (5656)	41.8 (6062)	630
32-B-GP100-2	12	75 (2.9)	330	420	3.4	3.1	—	27.3 (3959)	33.5 (4859)	40.2 (5830)	40.3 (5845)	630
32-B-GP100-3 (Control)	5	75 (2.9)	—	—	4.1	—	—	25.3 (3669)	32.5 (4713)	39.2 (5685)	41.8 (6062)	600
32-B-GP100-3	7.5	85 (3.3)	—	—	3.8	—	—	25.5 (3698)	31.3 (4539)	39.5 (5729)	43.0 (6236)	550
32-B-GP100-3	10	80 (3.1)	—	—	3.6	—	—	25.3 (3669)	32.0 (4641)	40.0 (5801)	41.5 (6019)	630
32-B-GP100-3	12	75 (2.9)	—	—	3.4	—	—	24.5 (3553)	30.5 (4423)	37.2 (5395)	38.3 (5555)	600
32-B-GP75FA25-4 (Control)	5	90 (3.5)	400	510	2.8	6.4	—	17.5 (2538)	23.8 (3452)	35.8 (5192)	42.8 (6207)	480
32-B-GP75FA25-4	7.5	75 (2.9)	400	510	3.1	4.5	—	18.2 (2640)	25.5 (3698)	38.8 (5627)	44.5 (6454)	510
32-B-GP75FA25-4	10	75 (2.9)	400	500	3.2	4.6	—	19.0 (2756)	25.8 (3742)	39.0 (5656)	44.5 (6454)	480
32-B-GP75FA25-4	12	70 (2.8)	370	470	3.2	4	—	20.0 (2901)	27.0 (3916)	38.7 (5613)	45.0 (6526)	480
32-B-GP75FA25-5 (Control)	5	80 (3.1)	—	—	3.2	—	—	16.8 (2437)	23.8 (3452)	35.7 (5178)	42.0 (6091)	490
32-B-GP75FA25-5	7.5	75 (2.9)	—	—	3.1	—	—	17.3 (2509)	23.5 (3408)	36.7 (5323)	43.3 (6280)	490
32-B-GP75FA25-5	10	70 (2.8)	—	—	3.2	—	—	16.8 (2437)	23.8 (3452)	36.2 (5250)	43.0 (6236)	490
32-B-GP75FA25-5	12	75 (2.9)	—	—	3.1	—	—	17.0 (2466)	22.0 (3191)	34.5 (5004)	41.3 (5990)	480
32-B-GP55FA25S20-6 (Control)	5	85 (3.3)	430	570	3.2	6.8	—	11.8 (1711)	18.8 (2727)	36.0 (5221)	41.5 (6019)	540
32-B-GP55FA25S20-6	7.5	90 (3.5)	440	570	3.1	5.7	—	12.5 (1813)	20.8 (3017)	38.5 (5584)	44.0 (6381)	590
32-B-GP55FA25S20-6	10	80 (3.1)	450	570	3.2	5.5	—	13.0 (1885)	20.8 (3017)	35.7 (5178)	40.8 (5917)	580
32-B-GP55FA25S20-6	12	80 (3.1)	410	530	3.1	5.5	—	13.8 (2001)	21.5 (3118)	36.8 (5337)	42.0 (6091)	600
32-B-GP55FA25S20-7 (Control)	5	80 (3.1)	—	—	3.2	—	—	12.0 (1740)	19.3 (2799)	36.5 (5294)	42.8 (6207)	560
32-B-GP55FA25S20-7	7.5	75 (2.9)	—	—	3.2	—	—	12.3 (1784)	20.3 (2944)	36.7 (5323)	43.5 (6309)	650
32-B-GP55FA25S20-7	10	85 (3.3)	—	—	3.2	—	—	12.0 (1740)	19.8 (2872)	35.8 (5192)	41.8 (6062)	600
32-B-GP55FA25S20-7	12	80 (3.1)	—	—	3.2	—	—	12.8 (1856)	21.3 (3089)	36.3 (5265)	41.8 (6062)	580
32-C-100GP-8 (Control)	4.5	80 (3.1)	330	433	2.9	3.0	13.9 (2016)	28.1 (4075)	37.0 (5366)	45.0 (6526)	49.8 (7222)	540
32-C-100GP-8	10	80 (3.1)	305	405	3.0	2.3	12.1 (1755)	25.7 (3727)	33.1 (4800)	43.1 (6251)	47.5 (6889)	490
32-C-100GP-8	12	75 (2.9)	310	410	2.6	2.4	14.5 (2103)	28.7 (4162)	35.0 (5076)	43.7 (6338)	47.6 (6903)	530
32-C-GP75FA25-9 (Control)	4.5	78 (3.1)	368	470	1.5	3.5	11.0 (1595)	25.1 (3640)	33.6 (4873)	44.9 (6512)	54.9 (7962)	490
32-C-GP75FA25-9	10	80 (3.1)	345	480	1.6	2.9	10.2 (1479)	21.8 (3162)	29.7 (4307)	40.8 (5917)	51.3 (7440)	490
32-C-GP75FA25-9	12	80 (3.1)	370	490	1.2	2.8	11.5 (1668)	24.5 (3553)	30.7 (4452)	41.0 (5946)	52.0 (7542)	510
32-C-GP60A40-10 (Control)	4.5	85 (3.3)	363	483	2.3	4.7	7.0 (1015)	17.2 (2495)	26.8 (3887)	40.9 (5932)	50.8 (7368)	540
32-C-GP60A40-10	10	80 (3.1)	340	470	2.4	3.4	6.9 (1001)	17.7 (2567)	28.8 (4177)	41.6 (6033)	47.3 (6860)	580
32-C-GP60A40-10	12	85 (3.3)	355	485	2.1	3.6	7.2 (1044)	19.4 (2814)	30.1 (4365)	42.1 (6106)	47.3 (6860)	590

Notes: 1 mm = 0.0394 in.; 1 MPa = 145 psi.

limestone content, as shown in Fig. 4(f) and 5(f). However, the correlations were not strong and had very low  $R^2$ . Moreover, considering the unaggregated concrete drying

shrinkage test results shown in Table 3, the measured absolute maximum drying shrinkage from the 67 mixture series was

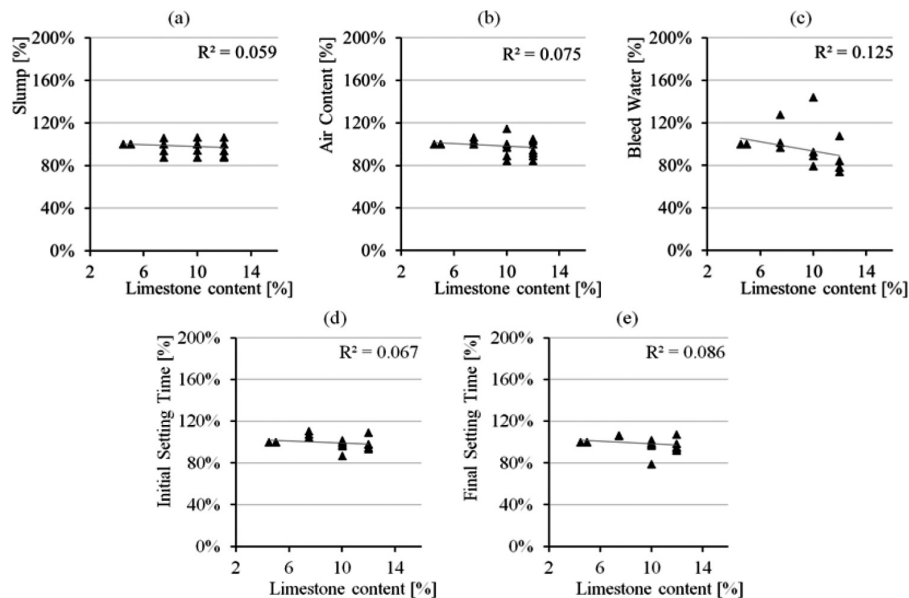


Fig. 2—Relative change of: (a) workability (slump); (b) air content; (c) bleed water; (d) initial setting time; and (e) final setting time to control samples for concrete Grade N20.

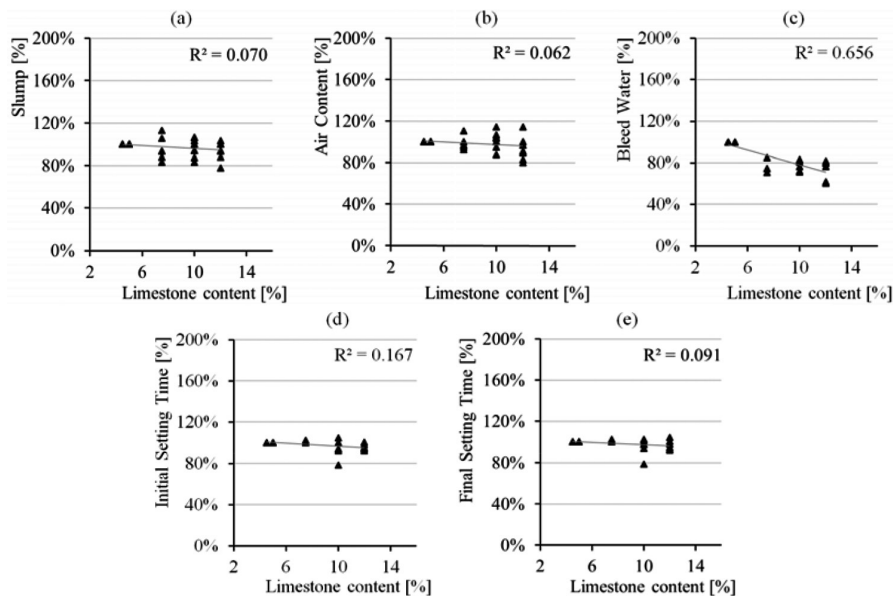


Fig. 3—Relative change of: (a) workability (slump); (b) air content; (c) bleed water; (d) initial setting time; and (e) final setting time to control samples for concrete Grade N32.

less 670 microstrains ( $\mu\epsilon$ ), which was significantly lower than the 1000  $\mu\epsilon$  limit specified by Australian Standard AS 1379.

In the second stage of the analysis, the compliance of concrete samples with the required properties specified by Australian Standards for normal-grade concrete was assessed. All data submitted showed that the control and test cements comply with the requirements of Australian Standard AS 1379. As can be seen from Table 4, the average of test values for different normal Grades N20 and N32 mixture series showed that different properties of concrete containing 10 and 12% limestone were comparable to the control samples containing 5%.

As can be seen from Table 4, the average test values for different mixture series (irrespective of their control samples and number of test repetitions) showed that the properties of 10 and 12% limestone concrete were similar to the control

samples. The absolute minimum and maximum test results from the samples prepared with cement containing 10 and 12% limestone are also presented in Table 4. As can be seen, at no point do any of the samples with the higher limestone content of 10 and 12% fail against the standard requirements.

In the third stage of the analysis, all properties of 10 and 12% limestone concrete were considered individually and compared to the same property of the control samples. The results for all concrete mixtures tested in this research—both control samples and those with 10 and 12% limestone mineral addition—were examined statistically (Table 5). The mean of the data population, the standard deviation of the data population (SD), and the number of data points were determined. By calculating standard error and critical  $t$  for the  $t$ -distribution of test results, statements as to the significance of the result of a student's  $t$ -test are presented.

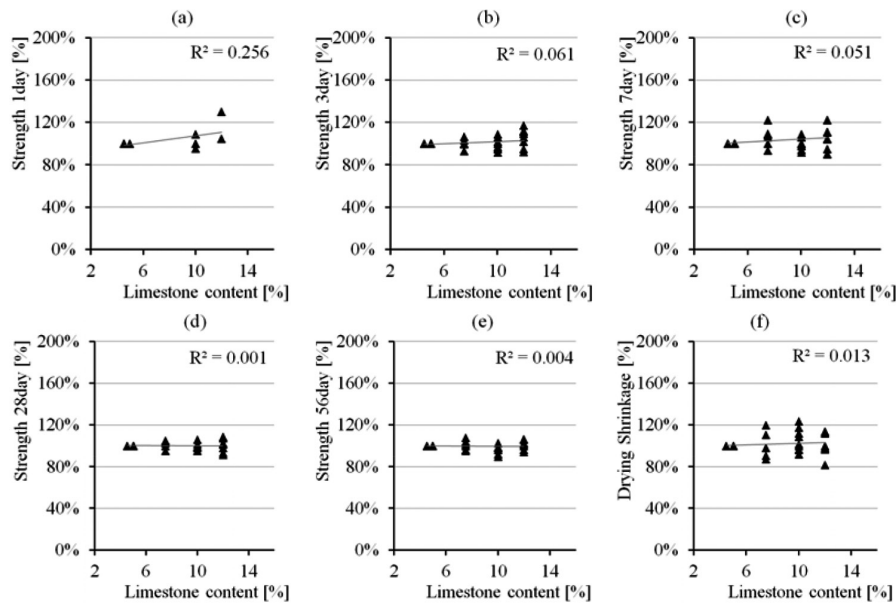


Fig. 4—Relative change of concrete compressive strength properties to control samples at: (a) 1 day; (b) 3 days; (c) 7 days; (d) 28 days; and (e) 56 days; and (f) drying shrinkage results for Grade N20.

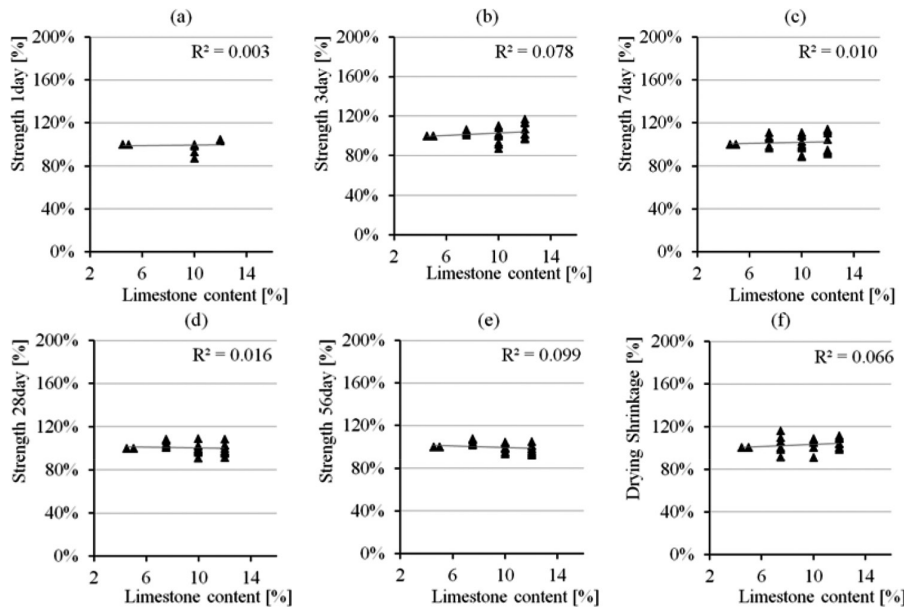


Fig. 5—Relative change of concrete compressive strength properties to control samples at: (a) 1 day; (b) 3 days; (c) 7 days; (d) 28 days; and (e) 56 days; and (f) drying shrinkage results for Grade N32.

It was observed that an increase in limestone content did not result in a statistically significant change in most properties of concrete. The decrease in bleed water, however, was found to be statistically significant for both Grades N20 and N32. It can be said with 95% confidence that bleed water was reduced due to increased limestone content in normal-grade concrete. This result confirmed the outcomes of the correlational study in the previous section, which showed the negative correlation between bleed water and limestone content of cement.

The observed reduction in slump and air content was found totally insignificant for 10% limestone content for both grades. For Grade N32, when prepared with 12% limestone cement, the reduction in slump and air content was found statistically significant. The slump mean for 12% limestone cement was decreased to 94.5% of the control

samples, while the critical value was 95%. Similarly, the air content mean for 12% limestone cement was 93.5% of the control samples, while the critical value was 94%. Considering other statistical results for slump and air content of Grades N20 and N32, it can be inferred that 10% limestone did not have a statistically significant effect on slump and air content, while the result for 12% showed a slight statistical significance.

In regard to the compressive strength results, no statistically significant effects were observed except for a 3.2% reduction in 56-day strength of the N20 grade prepared with 10% limestone cement and N32 grade did not present a similar or significant reduction. In addition, for Grade N32 prepared with 12% limestone, an increase in strength at early ages was observed; however, this increase was not confirmed

**Table 4—Normal-grade concrete test results for compliance with Australian Standard**

Property	Test method	Unit	AS 1379 Require- ments	Cement limestone content							
				5%	7.5%	10%			12%		
				Mean	Mean	Mean	Absolute minimum	Absolute maximum	Mean	Absolute minimum	Absolute maximum
Normal Grade N20 ( $f'_c = 20$ MPa [2900 psi])											
Slump	AS1012.3.1	mm (in.)	80 ± 20 (3.1 ± 0.8)	79 (3.1)	78 (3.1)	78 (3.1)	70 (2.8)	85 (3.3)	76 (3)	70 (2.8)	80 (3.1)
Initial setting time	AS1012.18	min	NA*	448	467	434	370	500	441	370	480
Final setting time	AS1012.18	min	NA*	583	587	558	480	630	555	460	610
Air content	AS1012.4.1	%	<5.0	3.9	3.7	3.9	3.0	5.0	3.6	3.0	4.3
Bleed water	AS1012.6	%	NA*	6.3	7.6	6.3	4.6	10.9	5.4	4.2	8.1
1-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	4.7 (682)	—	4.7 (682)	4.0 (580)	6.0 (870)	4.7 (682)	4.6 (667)	4.8 (696)
3-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	13.0 (1885)	13.0 (1885)	12.9 (1871)	7.9 (1146)	19.5 (2828)	13.6 (1972)	9.1 (1320)	21.0 (3046)
7-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	17.3 (2509)	18.7 (2712)	17.3 (2509)	13.5 (1958)	23.5 (3408)	18.5 (2683)	15.3 (2219)	26.0 (3771)
28-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	27.0 (3916)	28.1 (4075)	26.7 (3872)	24.6 (3568)	29.5 (4278)	27.2 (3945)	23.1 (3350)	31.5 (4568)
56-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	32.1 (4655)	32.1 (4655)	31.0 (4496)	28.5 (4133)	33.3 (4829)	32.3 (4684)	30.5 (4423)	33.8 (4902)
7-day CCS <sup>†,‡</sup>	AS1012.9	MPa (psi)	$f'_c > 9.0$ (1305)	15.1 (2190)	15.0 (2175)	15.1 (2190)	11.8 (1711)	NA <sup>§</sup>	15.8 (2291)	13.1 (1900)	NA <sup>§</sup>
28-day CCS <sup>†,‡</sup>	AS1012.9	MPa (psi)	$f'_c > 20.0$ (2901)	26.2 (3800)	26.8 (3887)	25.7 (3727)	23.7 (3437)	NA <sup>§</sup>	25.3 (3669)	21.5 (3118)	NA <sup>§</sup>
Drying shrinkage	AS1012.13	με	<1000	507	502	532	NA <sup>  </sup>	650	500	NA <sup>  </sup>	590
Normal Grade N32 ( $f'_c = 32$ MPa [4641 psi])											
Slump	AS1012.3.1	mm (in.)	80 ± 20 (3.1 ± 0.8)	82 (3.2)	79 (3.1)	80 (3.1)	70 (2.8)	85 (3.3)	77 (3)	70 (2.8)	85 (3.3)
Initial setting time	AS1012.18	min	NA*	394	397	360	305	450	358	310	410
Final setting time	AS1012.18	min	NA*	510	507	474	405	570	468	410	530
Air content	AS1012.4.1	%	<5.0	3.0	3.3	2.9	1.6	3.6	2.8	1.2	3.4
Bleed water	AS1012.6	%	NA*	5.4	4.7	3.8	2.3	5.5	3.6	2.4	5.5
1-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	10.5	—	9.8 (1421)	6.9 (1001)	12.1 (1755)	11.1 (1610)	7.2 (1044)	14.5 (2103)
3-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	19.5	18.7 (2712)	19.8 (2872)	12.0 (1740)	25.8 (3742)	20.9 (3031)	12.8 (1856)	28.7 (4162)
7-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	26.5	25.9 (3756)	27.3 (3959)	19.8 (2872)	33.1 (4800)	28.0 (4061)	21.3 (3089)	35.0 (5076)
28-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	38.4	38.5 (5584)	39.0 (5656)	35.7 (5178)	43.1 (6251)	38.9 (5642)	34.5 (5004)	43.7 (6338)
56-day CS <sup>†</sup>	AS1012.9	MPa (psi)	NA*	43.9	43.6 (6323)	44.6 (6468)	40.8 (5917)	51.3 (7440)	44.0 (6381)	38.3 (5555)	52.0 (7542)
7-day CCS <sup>†,‡</sup>	AS1012.9	MPa (psi)	$f'_c > 16.0$ (2320)	22.6	21.3 (3089)	24.6 (3568)	17.8 (2582)	NA <sup>§</sup>	24.7 (3582)	18.8 (2727)	NA <sup>§</sup>
28-day CCS <sup>†,‡</sup>	AS1012.9	MPa (psi)	$f'_c > 32.0$ (4641)	36.3	37.2 (5395)	37.5 (5439)	34.3 (4975)	NA <sup>§</sup>	37.1 (5381)	32.9 (4771)	NA <sup>§</sup>
Drying shrinkage	AS1012.13	με	<1000	548	560	564	NA <sup>  </sup>	670	556	NA <sup>  </sup>	630

\*No requirement.

†CS is compressive strength; CCS is characteristic compressive strength.

‡Characteristic compressive strength (CCS) is calculated at 95% level of confidence.

§Only the absolute minimum compressive strength results should be tested against the requirements of the Australian Standard.

||Only the absolute maximum drying shrinkage should be tested against the requirements of the Australian Standard.

Notes: 1 mm = 0.0394 in.; 1 MPa = 145 psi.

**Table 5—Normal-grade concrete test results analysis for 10% and 12% limestone content**

Property	General purpose (GP) with 10% limestone content									General purpose (GP) with 12% limestone content								
	Mean	SD*	Type of change	NOR†	ST Err‡	$t_{critical}$	CMV§		Statistical significance	Mean	SD*	Type of change	NOR†	ST Err‡	$t_{critical}$	CMV§		Statistical significance
							Min	Max								Min	Max	
Normal Grade N20 ( $f'_c$ = 20 MPa [2900 psi])																		
Slump	98.7%	5.2%	Decrease	9	1.70%	1.86	97%	103%	Insig	96.2%	6.6%	Decrease	8	2.30%	1.89	96%	104%	Insig
Initial setting time	96.8%	5.4%	Decrease	6	2.20%	2.02	96%	104%	Insig	98.5%	6.2%	Decrease	5	2.80%	2.13	94%	106%	Insig
Final setting time	96.1%	8.6%	Decrease	6	3.50%	2.02	93%	107%	Insig	97.2%	6.1%	Decrease	5	2.70%	2.13	94%	106%	Insig
Air content	97.9%	8.5%	Decrease	9	2.80%	1.86	95%	105%	Insig	96.2%	7.7%	Decrease	8	2.70%	1.89	95%	105%	Insig
Bleed water	96.8%	27.0%	Decrease	5	12.10%	2.13	74%	126%	Insig	<b>84.2%</b>	<b>13.4%</b>	<b>Decrease</b>	<b>5</b>	<b>6.00%</b>	<b>2.13</b>	<b>87%</b>	<b>113%</b>	<b>Sig</b>
1-day strength	101.2%	6.4%	Increase	3	3.70%	2.92	89%	111%	Insig	117.1%	17.8%	Increase	2	12.60%	6.31	20%	180%	Insig
3-day strength	98.8%	5.7%	Decrease	9	1.90%	1.86	96%	104%	Insig	105.2%	8.7%	Increase	8	3.10%	1.89	94%	106%	Insig
7-day strength	100.2%	5.5%	Increase	9	1.80%	1.86	97%	103%	Insig	107.3%	11.7%	Increase	8	4.10%	1.89	92%	108%	Insig
28-day strength	99.0%	3.2%	Decrease	9	1.10%	1.86	98%	102%	Insig	100.4%	6.0%	Increase	8	2.10%	1.89	96%	104%	Insig
<b>56-day strength</b>	<b>96.8%</b>	<b>4.0%</b>	<b>Decrease</b>	<b>9</b>	<b>1.30%</b>	<b>1.86</b>	<b>98%</b>	<b>102%</b>	<b>Sig</b>	100.9%	4.3%	Increase	8	1.50%	1.89	97%	103%	Insig
Drying shrinkage	105.2%	10.7%	Increase	9	3.60%	1.86	93%	107%	Insig	101.2%	11.0%	Increase	8	3.90%	1.89	93%	107%	Insig
Normal Grade N32 ( $f'_c$ = 32 MPa [4641 psi])																		
Slump	96.9%	7.7%	Decrease	10	2.40%	1.83	96%	104%	Insig	<b>94.5%</b>	<b>7.8%</b>	<b>Decrease</b>	<b>9</b>	<b>2.60%</b>	<b>1.86</b>	<b>95%</b>	<b>105%</b>	<b>Sig</b>
Initial setting time	94.8%	8.4%	Decrease	7	3.20%	1.94	94%	106%	Insig	<b>95.8%</b>	<b>3.0%</b>	<b>Decrease</b>	<b>6</b>	<b>1.20%</b>	<b>2.02</b>	<b>98%</b>	<b>102%</b>	<b>Sig</b>
Final setting time	96.1%	8.1%	Decrease	7	3.10%	1.94	94%	106%	Insig	97.1%	4.7%	Decrease	6	1.90%	2.02	96%	104%	Insig
Air content	101.1%	7.0%	Increase	10	2.20%	1.83	96%	104%	Insig	<b>93.5%</b>	<b>10.2%</b>	<b>Decrease</b>	<b>9</b>	<b>3.40%</b>	<b>1.86</b>	<b>94%</b>	<b>106%</b>	<b>Sig</b>
<b>Bleed water</b>	<b>77.8%</b>	<b>5.3%</b>	<b>Decrease</b>	<b>6</b>	<b>2.10%</b>	<b>2.02</b>	<b>96%</b>	<b>104%</b>	<b>Sig</b>	<b>73.4%</b>	<b>9.7%</b>	<b>Decrease</b>	<b>6</b>	<b>4.00%</b>	<b>2.02</b>	<b>92%</b>	<b>108%</b>	<b>Sig</b>
1-day strength	94.6%	5.9%	Decrease	4	3.00%	2.35	93%	107%	Insig	<b>103.9%</b>	<b>0.9%</b>	<b>Increase</b>	<b>3</b>	<b>0.50%</b>	<b>2.92</b>	<b>98%</b>	<b>102%</b>	<b>Sig</b>
3-day strength	99.4%	7.3%	Decrease	10	2.30%	1.83	96%	104%	Insig	<b>106.2%</b>	<b>7.3%</b>	<b>Increase</b>	<b>9</b>	<b>2.40%</b>	<b>1.86</b>	<b>95%</b>	<b>105%</b>	<b>Sig</b>
7-day strength	100.0%	7.5%	Decrease	10	2.40%	1.83	96%	104%	Insig	103.0%	9.9%	Increase	9	3.30%	1.86	94%	106%	Insig
28-day strength	99.5%	4.7%	Decrease	10	1.50%	1.83	97%	103%	Insig	99.5%	5.1%	Decrease	9	1.70%	1.86	97%	103%	Insig
56-day strength	99.0%	4.2%	Decrease	10	1.30%	1.83	98%	102%	Insig	97.6%	4.3%	Decrease	9	1.40%	1.86	97%	103%	Insig
Drying shrinkage	103.1%	5.5%	Increase	10	1.70%	1.83	97%	103%	Insig	<b>103.6%</b>	<b>5.0%</b>	<b>Increase</b>	<b>9</b>	<b>1.70%</b>	<b>1.86</b>	<b>97%</b>	<b>103%</b>	<b>Sig</b>

\*SD is standard deviation.

†NOR is number of results.

‡ST Err is standard error =  $SD/(NOR)^{0.5}$ ;  $t_{critical}$  is critical values of Student's  $t$ -distribution at 95%.§CMV is critical mean value = mean  $\pm$  ST Err  $\times t_{critical}$ .

||“Insig” is insignificant; “Sig” is significant.

by inferential analysis. Overall, the limited increase in compressive strength at early ages was determined to be statistically insignificant.

Drying shrinkage increased by 1 to 5% with an increase in limestone content; however, only Grade N32 prepared with 12% limestone content was found to be statistically significant, with a 3.6% increase in drying shrinkage. It should be noted that mixture designs for normal-grade concrete can be simply adjusted to present comparable fresh and hardened properties with the control samples. Moreover, it worth noting that an assessment should not be made on the basis of a statistical analysis alone, and that practical matters such

as test accuracy and compliance with standard requirements must also be considered in making the final decision.

In summary, the fresh and hardened results for samples prepared with higher limestone contents, demonstrated comparable properties with the control samples (5% limestone content) and there is no technical evidence to limit the manufacture of GP cement with up to 12% limestone content.

## SUMMARY AND CONCLUSIONS

This study has comprehensively reviewed the use of limestone mineral addition at levels up to 12% in GP cement. The review includes both a comprehensive test program and a



review of the technical literature to support the methodology and the test data obtained. Compliance studies indicated that normal-grade concrete prepared with 10 and 12% limestone content comply with Australian standards. Moreover, the inferential study confirmed that the increased limestone content did not impact concrete properties compared to the control samples. The result of this research supports the recommendation to increase the allowable limestone content of GP cement to a maximum of 12%. The influence of increased limestone addition on the properties examined in this research can be summarized as follows:

**Workability**—Workability was measured by concrete slump for a range of normal-grade concrete mixtures. No trend was evident with increasing limestone addition. The only statistically significant results, resulting in a 5.5% decrease in slump, was Grade N32 prepared with 12% limestone content. However, all samples complied with the 80 mm (3.1 in.) requirement. It is concluded that slump of normal grades of concrete is not affected by the change in limestone in the range of 5 to 12%.

**Bleed water**—Bleed water generally reduced with an increased limestone addition. The inferential studies confirmed limited reduction in bleed of normal grades of concrete.

**Air content and setting time**—The statistical examination of the test results arising from air content and setting time present comparable performance for normal grades of concrete prepared with cement containing limestone in the range of 5 to 12%. Only at 12% limestone content was a very minor reduction in the air content and setting times observed.

**Compressive strength**—Results did not present any strong relationship between limestone content and concrete strength at different testing ages. Individual results showed a very limited reduction of compressive strength (3.2%) of Grade N20 in 56 days, and similarly a slight increase (3 to 6%) in the early-age compressive strength of Grade N32.

**Drying shrinkage**—Drying shrinkage results were within 3.6% of the control samples for concrete prepared with 12% limestone cement. It was concluded that 12% limestone did not affect drying shrinkage of normal-grade (N20 and N32) concretes.

To conclude, it is recommended the allowable mineral addition in the Australian Standard AS 3972 for the Type GP cement be increased from 7.5 to 12%. It is estimated that the increase in limestone content of GP cement results in a 6% decrease in CO<sub>2eq</sub> emissions associated with the production of GP cement.

## AUTHOR BIOS

**James Mohammadi** is a Research Engineer for Cement Concrete & Aggregates Australia (CCAA), Sydney, Australia. He received his master's degree in civil engineering from the University of Technology, Sydney, Australia, in 2014. His research interests include cement manufacturing, concrete performance tests, and durability and structural design of concrete structures.

**Warren South** is the Director of Research and Technical Services for Cement Concrete & Aggregates Australia (CCAA). He received his PhD in civil engineering from the University of Wollongong, Wollongong, Australia, in 2009. His research interests include cement and concrete production, concrete durability, sustainability, and performance.

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